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EXTRASOLAR PLANET ECCENTRICITIES FROM SCATTERING IN THE PRESENCE OF RESIDUAL GAS DISKS

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ABSTRACT

Gravitational scattering between massive planets has been invoked to explain the eccentricity distribution of extrasolar planets. For scattering to occur, the planets must either form in – or migrate into – an unstable configuration. In either case, it is likely that a residual gas disk, with a mass comparable to that of the planets, will be present when scattering occurs. Using explicit hydrodynamic simulations, we study the impact of gas disks on the outcome of two-planet scattering. We assume a specific model in which the planets are driven toward instability by gravitational torques from an outer low mass disk. We find that the accretion of mass and angular momentum that occurs when a scattered planet impacts the disk can strongly influence the subsequent dynamics by reducing the number of close encounters. The eccentricity of the innermost surviving planet at the epoch when the system becomes Hill stable is not substantially altered from the gas-free case, but the outer planet is circularized by its interaction with the disk. The signature of scattering initiated by gas disk migration is thus a high fraction of low eccentricity planets at larger radii accompanying known eccentric planets. Subsequent secular evolution of the two planets in the presence of damping can further damp both eccentricities, and tends to push systems away from apsidal alignment and toward anti-alignment. We note that the late burst of accretion when the outer planet impacts the disk is in principle observable, probably via detection of a strong near-IR excess in systems with otherwise weak disk and stellar accretion signatures.

Subject headings: accretion, accretion disks — scattering — planets and satellites: formation — planetary systems: formation — planetary systems: protoplanetary disks

1. MOTIVATION

The eccentricity distribution of massive extrasolar planets beyond the tidal circularization radius is broad, with a median eccentricity $< e > \simeq 0.25$ (Marcy et al. 2005). Since giant planet formation models predict that the envelope is accreted when the planet has an almost circular orbit, the observed eccentricities are generally interpreted as evidence of evolutionary processes that occur subsequently. One possibility is that the same gravitational torques from the gas disk that drive orbital migration also excite eccentricity (Artymowicz et al. 1991; Ogilvie & Lubow 2003; Goldreich & Sari 2003; Moorhead & Adams 2008). Alternatively, the eccentricity may arise from gravitational instability within an unstable multiple system (Rasio & Ford 1996; Weidenschilling & Marzari 1996; Lin & Ida 1997). N-body experiments show that a wide variety of unstable initial conditions – which can include systems with two, three or many giant planets – evolve under scattering to yield an eccentricity distribution similar to that observed (Chatterjee et al. 2007; Juric & Tremaine 2007). The agreement between theory and observations supports the scattering scenario, though other possibilities are not ruled out.

To date, most studies of planet-planet scattering have considered purely gravitational evolution from gas-free initial conditions. Gas has been ignored primarily for reasons of computational necessity, since fairly robust arguments suggest that at least *small* amounts of gas are likely to survive to the epoch when scattering occurs (planetesimal disks will also be present, though these will likely be dynamically important only in systems similar to the Solar System, in which at least some giant planets at large radii have low envelope masses). In particular, for two-planet systems most initial separations within the boundary that is Hill stable for all time (Gladman 1993) are unstable on very short time scales. Realistically, an unstable two planet system is therefore likely to arise only if the planets are driven toward such a state, for example due to gas disk migration. Efficient migration requires a disk mass that is of the same order as the planet mass. Multiple planet systems with $N_p > 2$ exhibit broader instability regions, but even in this case the most likely scenario is that instability sets in once eccentricity damping due to the presence of gas becomes small enough. Again, this will occur once (to order of magnitude) the gas disk mass falls to the level of the planet mass, and scattering is likely to occur in an environment that is gas poor but not gas free.

In this paper we use hydrodynamic simulations to study the influence of low mass residual gas disks on the outcome of gravitational scattering. As noted above, there are many possible scenarios that yield different initial conditions for scattering experiments – here we adopt a simple model that is computationally tractable. We assume that two Jupiter-mass planets form on well-separated circular orbits. Models of giant planet formation suggest that the onset of runaway accretion occurs

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TABLE 1
SIMULATION PARAMETERS

Case	d_{close} (AU)	$m_{out,f}$ (M_J)	L_{acc}^{max} ($10^{32} erg\ s^{-1}$)	$< L_{acc} >$ ($10^{32} erg\ s^{-1}$)	ζ_f (ζ_{crit})
A	0.00094	1.48	6.26	1.76	1.027
B	0.0075	1.54	11.37	2.54	1.040
C	0.044	1.40	11.51	2.75	1.005
D	0.11	1.52	18.82	4.68	1.034
E	0.30	1.61	18.36	5.82	1.045

NOTE. — The closest approach during the initial scattering is d_{close}. Subscript f refers to the quantity at the end of the simulations, 10^4 yr. $< L_{acc} >$ is the mean accretion luminosity for the first 500 years of the simulation.

when the cores attain a mass of 10 $M_\oplus$ (Hubickyj et al. 2005), and, since neighboring cores are likely to form with a separation of $\sim$ 10 mutual Hill radii (Kokubo & Ida 1998), this suggests that plausible initial separation ratios are $\simeq$ 1.3 or greater. If the gas disk interior to the outer planet is relatively weak migration driven by the residual outer gas results in convergence of the orbits. The initial separation alluded to above lies close to the 3:2 resonance, so depending upon the precise initial separation convergent migration might result in resonance crossing. If the resonance *is* encountered, the result can either be trapping into resonance (Lee & Peale 2002; Snellgrove et al. 2001; Kley et al. 2005)[4] or, if the disk is turbulent (Adams et al. 2008), avoidance of trappping and ongoing convergence of the orbits. In the latter case the outer planet continues to migrate inward on a viscous time scale until the separation of the planets is driven past the Hill stability criterion, and a scattering event occurs. The goal of this paper is to answer the question: what effect does the remnant disk now have on the scattering planetary system?

2. SIMULATION METHOD AND INITIAL CONDITIONS

Hydrodynamic simulations of the disk over dynamically interesting time scales are computationally difficult. In this preliminary study we consider only a small number of cases, and set up the initial conditions so that scattering occurs early in the simulation. Using purely N-body runs, we first identified a large number of initial conditions in which two Jupiter mass planets, orbiting a Solar mass star on nearly circular orbits separated by 2.5 to 3 mutual Hill radii, are about to experience a first close encounter. For realistic migration rates (Armitage 2007) instability is likely to set in at approximately this separation. The orbital radius of the inner planet was set to 3 AU. The planets were nearly coplanar, with small inclinations $i \lesssim 1^\circ$. We chose five initial conditions from these N-body runs spanning a range in the closest approach distance attained during the first encounter, summarized in Table 1.

We evolve the initial conditions for 10^4 yr both as a purely N-body system, and hydrodynamically including the influence of an external gas disk. The remnant disk is assumed to extend from 5-10 AU with a surface density profile $\Sigma(r) = \Sigma_0 r^{-3/2}$, normalized so that the gas disk contains one Jupiter mass of gas. This setup is quite similar to the scenario considered

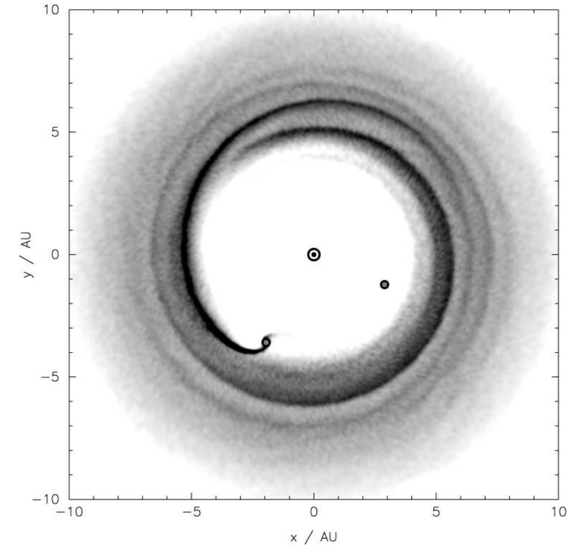

FIG. 1.— An example snapshot from case C illustrating the interaction between the outer planet and the disk. Plotted (using the program `splash,` Price 2007) is the column density, with the star (*dotted circle*) at the center and the two planets (*filled circles*) in orbit. The outer planet has induced density waves in the disk, from which it is accreting gas. This snapshot is $\sim$ 30 years after the close encounter between the planets.

by Moorhead & Adams (2005), in which two-planet systems that had cleared an inner gap were driven toward instability via Type II migration of the outer planet. These authors include the effect of a remnant disk on planet-planet scattering via an eccentricity damping prescription. Likewise, Chatterjee et al. (2007) studied the damping effect of a disk on three-planet scattering by coupling a planet-disk torque prescription with a 1-D disk model. In most of our models we assume that the inner disk is weak enough as to be neglected. In the regime we consider considerable depletion of the inner disk is likely, since the angular momentum of the planets is large enough to significantly retard the inflow of the outer disk while the inner disk continues to accrete on the normal viscous time scale. However, full depletion of the inner disk is only an approximation[5], and recent calculations suggest that some gas will either survive in the inner region or flow past the planets from the outer disk to resupply the inner disk (Crida & Morbidelli 2007; Lubow & D'Angelo 2006). We therefore ran one additional simulation to ascertain the effect of a small mass of gas interior to the planets on the results. Using the results of Lubow & D'Angelo (2006), we estimated that reasonable amounts of material in the depleted inner disk will likely be of the order 10% of the initial disk profile (Lubow & D'Angelo 2006), so that the inner disk has $\Sigma(r) = 0.1\Sigma_0 r^{-3/2}$. If the inner disk extends from 0.75 - 2 AU, it contains $\sim 0.06 M_J$ of material, much less than the outer disk. If the inner planet scatters into this inner remnant a small amount of eccentricity damping and mass loading onto the planet could occur.

We evolve the system using the GADGET-2 smoothed particle hydrodynamics (SPH) code (Springel 2005), modified so that the star and planets behave as sink particles (Bate et al. 1995). The accretion radius of the

[4] The existence of a number of known resonant pairs of planets supports the idea that trapping occurs in at least some cases.

[5] Unless magnetic effects (Chiang & Murray-Clay 2007) or photoevaporation (Clarke et al. 2001) operate and clear a true cavity out as far as the radius of the inner planet.

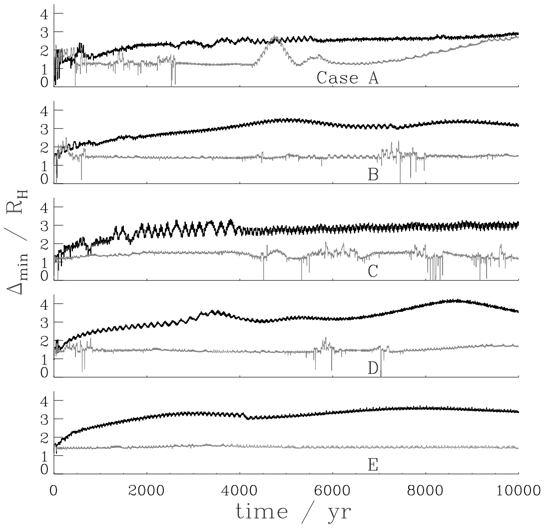

FIG. 2.— The minimum separation (equation 1) for each case in units of mutual Hill radii. *Thick*: the simulations with the gas disk. *Thin*: the same initial conditions run with no disk.

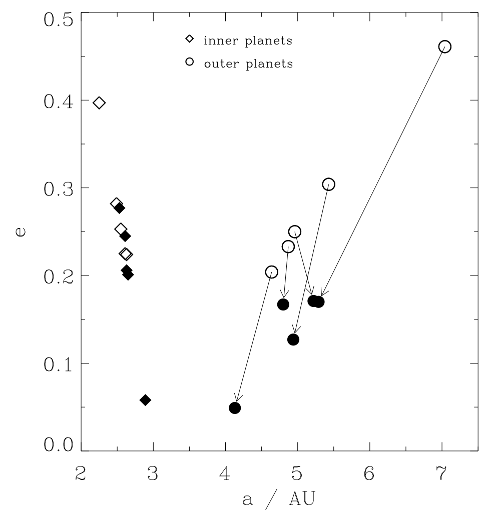

FIG. 3.— The mean values of the eccentricities and semi-major axes for all the simulations. *Filled symbols*: simulations with disks. *Open symbols*: simulations with no disks. Arrows connect the same initial conditions with and without disks for the outer planets.

planets is set to $\sim 50 R_J$. The star and planets interact with each other and the gas particles only via gravity, which is effectively unsoftened. A further modification to the code was made to ensure that the force between the star and planets is computed directly, and not with a tree-code approximation. For the runs presented here the disk is represented by $\sim 1.75 \times 10^5$ particles. At this resolution the Hill radius of the planets is resolved by several SPH smoothing lengths throughout the disk. We performed a resolution test by placing a single planet on an eccentric orbit that initially made excursions into the disk at apastron. The evolution of the planet's mass, eccentricity, and semi-major axis showed good agreement between resolutions of 1.5×10^5 and 3.0×10^5 particles. Figure 1 shows an example of one of our runs, showing the interaction of the outer planet with the disk approximately 30 years after the scattering.

3. RESULTS

Following the scattering event, we evolve the system hydrodynamically up to the time when the separation of the planets is great enough that – *in the absence of gas* – they would be Hill stable. This requires a relatively short integration of the order of 10^4 yr in duration. It would be desirable to continue the hydrodynamic simulation until all of the gas has been dispersed, but this is both computationally more difficult and would require the addition of additional physics (such as photoevaporation) describing the final clean-up of the gas disk. In the paper, we instead study the longer term evolution using N-body calculations that include an approximate treatment of the effects of gas disk damping on planetary eccentricity.

3.1. *Short-term evolution*

Figure 2 shows how the separation of the planets evolves with time in runs with and without gas. As a measure of the stability of the systems, we calculate the minimum separation, defined by the instantaneous values of the semi-major axes a and eccentricities e of the inner and outer planets by

$$\Delta_{min} = a_{out}(1 - e_{out}) - a_{in}(1 + e_{in}). \tag{1}$$

Figure 2 shows this quantity as a fraction of the mutual Hill radius

$$R_H = \left(\frac{m_{in} + m_{out}}{3M_\star}\right)^{1/3} \bar{a}, \tag{2}$$

where $\bar{a}$ is the average of the planet's semi-major axes and $M_\star$ is the stellar mass. For nearly-circular planets, the system is Hill stable when the orbital parameters satisfy $\Delta_{min} \gtrsim 3.5 R_H$ (Gladman 1993). Though the orbits in these simulations are moderately eccentric, we use this measure as a intuitive guide to short-term stability. Marchal & Bozis (1982) give a general condition for Hill stability, parameterized by a combination of the bodies' masses and the system's angular momentum and energy, $\zeta \propto L^2 E$. A critical value ζ_{crit} can be found, above which the system is stable. In the non-dissipative case L and E are integrals of motion, and all of our simulations begin below the critical value. With dissipation in the form of the gas disk, the energy and angular momentum of the three bodies are no longer constant, and ζ can evolve. In table 1 we give the value of ζ as a fraction of the critical value at the end of the simulations. All of the dissipative cases have achieved Hill stability at 10^4 yr.

When no gas is present, the systems do not move toward stability over the timescale simulated, and all but one of them (case E, which is likely unstable on a somewhat longer timescale because of its larger close approach distance) continue to undergo strong scattering interactions. Case A with no disk appears to be moving toward a more stable configuration as measured by the minimum separation, but the measure of Hill stability ζ remains as it must at its initial value, in the unstable regime. The simulations including the remnant disk all follow the same general trend toward an increasing level of stability as measured by Δ_{min}/R_H. After the first 100 years of evolution, none of the systems with gas present undergo encounters with $r_{enc} < R_H$, whereas the non-dissipative runs continue to undergo strong interactions.

In Figure 3 we plot the mean values of a and e over the span of the simulations for the different cases, with

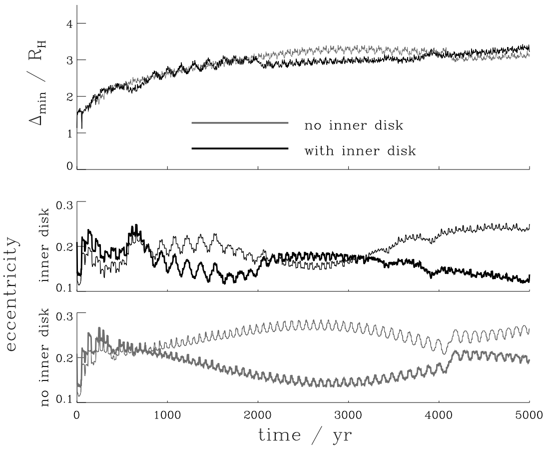

FIG. 4.— Comparison between case E with and without an inner disk. *Top*: the minimum separation (equation 1) for the two cases. Both have reached Hill stability by 5000 yr. *Bottom two panels*: the eccentricities of both planets for each case. The two planets are identified by thick and thin lines. The details of the eccentricity evolution differ when an inner disk is added, though the final result in the sense of stability is very similar.

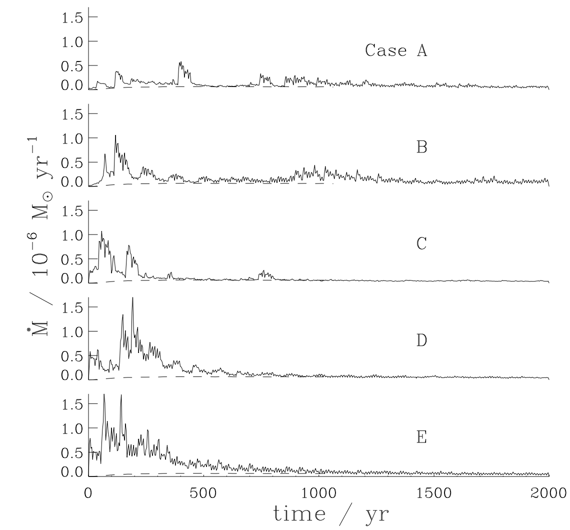

FIG. 5.— The accretion rate of the outer planet for each case, for the first 2000 years of the simulation. Also plotted (*dashed*) is a reference accretion rate in the absence of scattering.

and without the gas disk. While the inner planets show no clear separation in distribution, there is a consistent difference in eccentricity for the outer planets. The arrows connect the properties of the outer planet for each case, with and without remnant disks. In each instance, the simulation with a disk ends up at a lower eccentricity. The effect of the disk on the inclination evolution of the systems is much less clear, with no consistent trend appearing in our simulations.

We ran case E with the addition of an inner disk as well. Case E was chosen because its inner planet had the smallest periastron post-scattering, so that any effect of accretion from the inner disk would be maximized. The total angular momentum of the inner disk we simulated is $\sim$4% of the inner planet's orbital angular momentum, and we would expect the change in eccentricity associated with accreting this material to be small. In figure 4 we compare the evolution of the orbits with the different disk profiles. The details of the semi-major axis and eccentricity evolution between the two realizations are different, as the initial evolution of the inner planet is changed and sets the system on an altered path. The separation measure Δ_{min} shows a very similar evolution, however, with the same trend toward stability. As in the case with no inner disk, the outer planet accretes significantly from the exterior disk and circularizes. At 5000 years after the close encounter, the system has reached Hill stability ($\zeta/\zeta_{crit} = 1.033$) and the inner disk has been completely disrupted. The further evolution of the system will be driven by accretion onto the outer planet. We conclude that the presence of a depleted inner disk is unlikely to significantly affect the results of our simulations.

In contrast to dynamical friction, resonant interaction with the gas disk, or ejection of planetesimals, the stabilizing influence of these gas disks is due to the accretion of material by the outer planet. As it makes excursions into the disk near its apastron, it is accreting material with higher specific angular momentum, which causes its eccentricity to decrease. This effect is therefore dependent on enough material being present in the disk. Tests with 0.1 M_J of disk material showed very little difference from the runs with no gas present. By the end of the 10^4 yr run of the simulations the mass remaining in the disk has been reduced to $\sim 0.2{-}0.4 M_J$, while the outer planet has gained mass ($m_{out} \sim 1.5 M_J$, see Table 1). Due to the expense of the hydrodynamic simulations, we are unable to extend the runs over disk-driven migration timescales. We cannot directly guarantee that further viscous evolution of the disk will not push the planets back toward instability, and restart the whole cycle. However, this possibility is unlikely. Once the disk mass drops significantly below the planet mass the rate of migration is suppressed, though the exact degree depends upon the disk structure (e.g. Armitage 2007). The damage done to the outer disk by the initial scattering and subsequent accretion will have reduced the migration rate by a factor of several, making it unlikely that the disk will be able to push the system back toward instability during its remaining lifetime. A second round of instability is even less likely given the fact that photoevaporation of a sub-Jupiter mass gas disk by direct stellar illumination occurs on a rapid time scale (Alexander et al. 2006).

The accretion levels during the outer planet's initial interactions with the disk, when its eccentricity is damped most rapidly, are quite high. In figure 5 we show these rates for the first 2000 years of the simulations, i.e. immediately after the first scattering event. The cases with the weakest initial encounters exhibited deeper penetration into the disk, and have higher accretion rates than the cases with stronger interactions. With the exception of cases A and B, which show secondary bursts of accretion at $\sim$ 1000 years, the main accretion onto the planets occurs over the first 500 years of the simulations. As a reference accretion rate, we ran a simulation with a single planet orbiting at the 2:1 resonance with the inner edge of the disk for 1000 yr. This rate is plotted in figure 5 as well, and has a mean value $\sim 5 \times 10^{-8}$ M$_\odot$ yr^{-1}.

3.2. *Long-term evolution*

We terminated our SPH simulations with the inner planet on an eccentric orbit (typically $e \sim 0.2 - 0.3$)

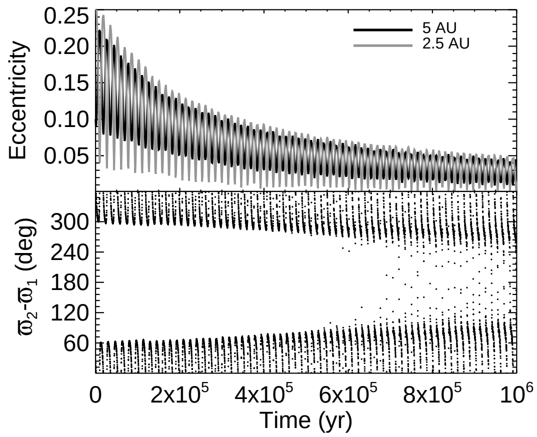

FIG. 6.— Long-term orbital evolution of two Jupiter-mass planets with a drag force being applied to the outer planet. *Top panel*: Eccentricities of the inner (*grey line*) and outer (*black line*) planets in time. *Bottom panel*: the relative apsidal angle, i.e. the angle between the longitudes of pericenter of the two planets, $\varpi_1 - \varpi_2$.

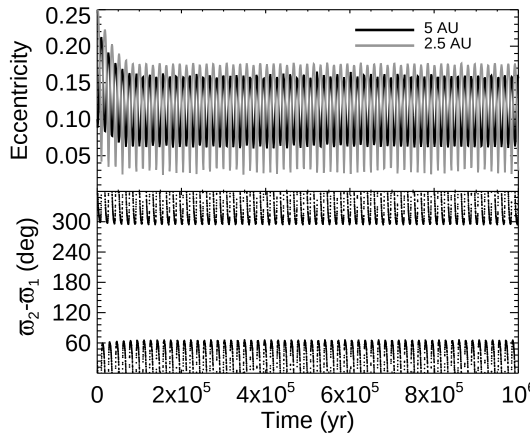

FIG. 7.— Long-term orbital evolution of two Jupiter-mass planets with a time-dependent drag force applied to the outer planet. The drag force decreases linearly to zero after 10^5 years and no drag is applied for the rest of the simulation.

and the outer planet still interacting with the remnant gaseous disk, though much more weakly than immediately after the scattering encounter. The lifetime of the remnant gaseous disk is uncertain: 10^{5-6} yr is a reasonable estimate based on models of dissipation via photoevaporation (Clarke et al. 2001; Alexander et al. 2006) and observational constraints (Simon & Prato 1995; Wolk & Walter 1996). Given that the outer planet is experiencing orbital damping and is also gravitationally interacting with the inner planet, an interesting question is whether the inner planet's eccentricity can be decreased. We therefore investigate the long-term dynamical evolution of these systems.

We model the system using the hybrid integrator `Mercury` (Chambers 1999). The physical scenario that we have in mind is that the eccentricity of the outer planet will be damped on long time scales via resonant interaction with the remaining gas disk, once it has settled down following the perturbation induced by the scattering. The exact form of the damping is not likely to be critical, so for simplicity we use a method that we have tested for other applications and apply a drag force to the outer planet in the form of a headwind which is proportional to the difference in velocity between the planet and the gas (which is assumed to be partially pressure supported, as in Thommes et al. 2003). This force is therefore equivalent to aerodynamic drag (Adachi et al. 1976). For our purposes we treat the strength of the damping as a free parameter, and calibrate the resulting eccentricity damping to match the damping of the outer planet in our SPH simulations. The effect of this force is to damp e on a timescale of a few times 10^4 years with little damping of a, as long as e is less than ~ 0.2. We therefore believe that our implementation is a reasonable approximation.

Figure 6 shows the evolution of two Jupiter-mass planets for a case that started with the inner planet with a = 2.5 AU and e = 0.2 and the outer planet at 5 AU with $e = 0.1$. The outer planet's eccentricity is quickly excited by the inner planet and the two planets undergo regular secular oscillations with a period of about 15,000 years. The initial amplitude of eccentricity oscillations is close to the inner planet's starting eccentricity, and the two values remain out of phase. The damping decreases the eccentricities of both planets in time, but does not affect the secular frequency. At the end of the simulation, the inner/outer planets have median eccentricities of 0.036/0.032. The damping also affected the planets' apsidal aligment, as measured by the difference in the longitudes of pericenter, i.e., $\varpi_1 - \varpi_2$. The two planets quickly became locked in libration about apsidal alignment ($\varpi_1 - \varpi_2 = 0$), but the libration amplitude increased in time until the nodes began to occasionally circulate after $\sim 6 \times 10^5$ years. For all the configurations that we tested, evolution moved the planets away from apsidal alignment and toward anti-alignment. For cases in which the outer planet started with $e = 0$, the system quickly tended toward anti-alignment and the amplitude of libration decreased steadily to from > 90 deg at early times to less than 50 deg after 1 Myr (see Chiang & Murray 2002).

The finite lifetime of the gaseous disk may limit the damping of the eccentricity of the outer, and therefore also inner, planet. The case from figure 6 assumed constant damping from the disk over 1 Myr. However, the outer disk is being depleted by both accretion onto the outer planet and photoevaporation. Figure 7 shows the evolution of the same two planets from figure 6 but assuming the damping dissipated linearly from its default value to zero after 10^5 years, a more reasonable value for the length of the final stage of disk dissipation (e.g. Clarke et al. 2001; Alexander et al. 2006). Eccentricities of the planets in figure 7 are far less damped than in figure 6: the median final eccentricities of the inner/outer planets are 0.127/0.12. Note that for the case of no damping, the median final eccentricities of the inner/outer planets are 0.24/0.14. Thus, even a short period of damping can reduce eccentricities. Note also that the weaker damping has slightly increased the libration amplitude but not enough to cause the apses to circulate. We regard this second setup, with a limited amount of damping, as the more realistic scenario. The remnant disk mass is reduced by the initial planet-disk interactions, and estimates of the photoevaporation timescale are closer to 10^5 than 10^6 yr.

The known extra-solar multi-planet systems are preferentially located close to the separatrix between apsi-

dal circulation and libration (Barnes & Greenberg 2006). Near-separatrix behavior is characterized by one of the planets periodically reaching an $e = 0$ state (e.g. Ford et al. 2005). The strong damping experienced by the system in figure 6 has driven the system from libration to a near-separatrix state, whereas the system from figure 7 is steadily librating. For cases which started with a zero eccentricity outer planet, the situation is reversed: simulations that experienced only a small amount of damping remained close to the separatrix but those that were strongly damped were driven to low-amplitude apsidal libration about anti-alignment. Thus, interactions between planets during this phase of a low-mass, remant gas disk may play an important role in establishing the final apsidal alignment of planetary systems.

4. DISCUSSION

The expense of the hydrodynamic simulations means that we have been able to run only a handful of realizations of scattering in the presence of gas, and as a consequence it is unwise to draw definitive conclusions. Nonetheless we find, as expected, that remnant disks that have masses comparable to the masses of the giant planets *do* influence the outcome of gravitational scattering, primarily via eccentricity damping that occurs due to accretion when planets intrude upon the gas disk. If, as we have assumed, the remnant gas lies exterior to the orbit of the outermost planet, damping when the planet enters the disk tends to increase the planetary separation and stabilize the system against close encounters and possible ejection of one of the planets. The stabilization occurs rapidly enough that we were able to evolve the systems with gas up to the point where they would plausibly be Hill stable.

The observed eccentricity distribution of extrasolar planets[6] matches the theoretically predicted one *from simulations that do not include gas* (Chatterjee et al. 2007; Juric & Tremaine 2007). If gas is implicated in driving planetary systems toward instability, its effect on the subsequent dynamics cannot be so strong as to ruin this agreement. We find that this is plausible. Specifically, models computed with an exterior disk whose mass equals that of the planets yield inner planet eccentricities that are comparable to those achieved in the absence of gas. Since radial velocity surveys favor the detection of planets at smaller orbital radii, the observed sample today is likely dominated by planets which would have been unaffected by gas during the scattering process. Conversely, we find that the eccentricity of the outer planet is significantly damped by accretion of gas once it enter the disk. The dynamical dominance of accretion over other damping mechanisms is likely the most robust result of this paper.

Although we have only considered one specific scattering scenario, it seems plausible that the generic effect of residual gas disks will be to increase the fraction of retained rather than ejected planets following scattering. If so, analysis of the abundance of multiple planets ought to provide the strongest constraints on models of this type. If the specific model for migration and scattering we have used were actually commonplace in extrasolar planetary systems, we would expect to find a high fraction of multiple planet systems in which the outer planet had a lower eccentricity than the inner planet. Observationally, it is known that there are hints for additional companions in many systems that host known planets (Wright et al. 2007), but the quantitative statistical analysis necessary to place limits on their masses and periods (analogous to the work of Cumming et al. 2008 for single planets) has not, to our knowledge, been attempted. Our impression is that while our toy model – in which the hypothetical outer planet has the same mass as the detected inner one – could already be ruled out observationally, a more realistic scenario in which the outer planet was modestly less massive probably remains viable. More extensive theoretical work will be needed to quantify the extent to which residual gas disks increase the predicted fraction of multiple systems after scattering.

On Myr timescales, the inner planet's eccentricity can be damped indirectly by the remnant gaseous disk via excitation of the outer planet and subsequent dissipation. The lifetime of the remnant disk is uncertain, but is probably $\sim 10^5$ years (Simon & Prato 1995; Wolk & Walter 1996; Clarke et al. 2001; Alexander et al. 2006). Given the large eccentricity of the inner planet and the relative proximity of the outer planet, there is strong secular coupling and eccentricity oscillations are induced. The damping of the outer planet by the remnant gas disk tends to push the system away from apsidal alignment and toward anti-alignment; the amount of damping depends on the disk lifetime. Depending on the starting configuration, strong damping can produce systems that are near the apsidal separatrix (Barnes & Greenberg 2006), circulating, or librating about anti-alignment. However, strong damping should not produce systems that librate about alignment. In cases with relatively little damping, the apsidal alignment is weakly affected, although eccentricities can be modestly reduced (see figure 7).

Finally, we note that the accretion rate onto the planet when the planet first enters the disk is rather high. This gas will, in reality, join a circumplanetary disk, and how quickly it is accreted by the planet will depend upon the evolution of that disk. However, it is clear that the luminosity of the planet could be large due to the implied late burst of accretion. Naively estimating the accretion luminosity as $L_{acc} \sim GM_p\dot{M}/R_p$, we find that for Jovian parameters the luminosity over the first 500 yr is of the order of 10^{32}-10^{33} erg s^{-1}. Since the accreted gas has angular momentum, the mass inflow onto the planet would be buffered by a circumplanetary disk, though only modestly since the viscous timescale of such disks is typically of the order of 10^3 yr or less (Canup & Ward 2002). Unlike the main envelope accretion event that occurs in core accretion models for giant planet formation, this late burst of accretion is in principle observable (as a near-IR excess without matching stellar accretion signatures) since the accretion luminosity of the circumstellar

[6] A detailed study of possible selection biases in the Keck planet search (Cumming et al. 2008) shows that the survey is complete for velocity amplitudes $K > 20$ ms^{-1} and $e < 0.6$. The "observed" distribution is therefore a reasonable proxy for the true distribution in the sense that neither low nor moderately high e objects are systematically missed. There may, however, be some upward bias to the derived eccentricities of detected planets in cases where the measurement signal to noise is relatively low (Shen & Turner 2008).

disk at this epoch is small. If we assume that late accretion is detectable for 10^3 yr, and occurs in 10-100% of young stars, then we would need to survey 10^4 to 10^5 systems to have a chance of directly observing the last stage of giant planet formation. Surveys of this magnitude are well beyond current capabilities, but are not inconceivable in the future.

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